

PHOSPHOR-COATED LIGHT EMITTING DIODES INCLUDING TAPERED SIDEWALLS, AND FABRICATION METHODS THEREFOR

Cross-Reference to Provisional Application

This application claims the benefit of provisional Application No. 60/411,980, filed September 19, 2002, entitled *Phosphor-Coated Light Emitting Diodes Including Tapered Sidewalls, and Fabrication Methods Therefor*, assigned to the assignee of the
5 present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein.

Field of the Invention

This invention relates to microelectronic devices and fabrication methods
10 therefor, and more particularly to light emitting diodes (LEDs) and fabrication methods therefor.

Background of the Invention

Light emitting diodes are widely used in consumer and commercial
15 applications. As is well known to those having skill in the art, a light emitting diode generally includes a diode region on a microelectronic substrate. The microelectronic substrate may comprise, for example, silicon, gallium arsenide, gallium phosphide, alloys thereof, silicon carbide and/or sapphire. Continued developments in LEDs have resulted in highly efficient and mechanically robust light sources that can cover
20 the visible spectrum and beyond. These attributes, coupled with the potentially long service life of solid state devices, may enable a variety of new display applications, and may place LEDs in a position to compete with the well entrenched incandescent and fluorescent lamps.

One measure of efficiency of LEDs is the cost per lumen. The cost per lumen
25 for an LED may be a function of the manufacturing cost per LED chip, the internal quantum efficiency of the LED material and the ability to couple or extract the generated light out of the device. An overview of light extraction issues may be found in the textbook entitled *High Brightness Light Emitting Diodes* to Stringfellow

et al., Academic Press, 1997, and particularly Chapter 2, entitled *Overview of Device Issues in High-Brightness Light Emitting Diodes*, to Craford, at pp. 47-63.

Light extraction has been accomplished in many ways, depending, for example, on the materials that are used to fabricate the diode region and the substrate. For example, in gallium arsenide and gallium phosphide material systems, a thick, p-type, topside window layer may be used for light extraction. The p-type window layer may be grown because high epitaxial growth rates may be possible in the gallium arsenide/gallium phosphide material systems using liquid and/or vapor phase epitaxy. Moreover, current spreading may be achieved due to the conductivity of the p-type topside window layer. Chemical etching with high etch rates and high etch selectivity also may be used to allow the removal of at least some of the substrate if it is optically absorbent. Distributed Bragg reflectors also have been grown between an absorbing substrate and the diode region to decouple the emitting and absorbing regions.

Other approaches for light extraction may involve mechanical shaping or texturing of the diode region and/or the substrate. However, it may be desirable to provide other light extraction techniques that can allow further improvements in extraction efficiency. Moreover, it may be desirable to increase the area of an LED chip from about 0.1 mm² to larger areas, to thereby provide larger LEDs. Unfortunately, the effectiveness of these shaping techniques may not be maintained as the chip dimensions are scaled up for higher power/intensity and/or other applications.

Much development interest and commercial activity recently has focused on LEDs that are fabricated in and/or on silicon carbide, because these LEDs can emit radiation in the blue/green portions of the visible spectrum. See, for example, U.S. Patent 5,416,342 to Edmond et al., entitled *Blue Light-Emitting Diode With High External Quantum Efficiency*, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein. There also has been much interest in LEDs that include gallium nitride-based diode regions on silicon carbide substrates, because these devices also may emit light with high efficiency. See, for example, U.S. Patent 6,177,688 to Linthicum et al., entitled *Pendeoepitaxial Gallium Nitride Semiconductor Layers On Silicon Carbide Substrates*, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein.

In such silicon carbide LEDs and/or gallium nitride LEDs on silicon carbide, it may be difficult to use conventional techniques for light extraction. For example, it may be difficult to use thick p-type window layers because of the relatively low growth rate of gallium nitride. Also, although such LEDs may benefit from the use of
5 Bragg reflectors and/or substrate removal techniques, it may be difficult to fabricate a reflector between the substrate and the gallium nitride diode region and/or to remove at least part of the silicon carbide substrate.

U.S. Patent 4,966,862 to Edmond, entitled *Method of Production of Light Emitting Diodes*, assigned to the assignee of the present application, the disclosure of
10 which is hereby incorporated herein by reference in its entirety as if set forth fully herein, describes a method for preparing a plurality of light emitting diodes on a single substrate of a semiconductor material. The method is used for structures where the substrate includes an epitaxial layer of the same semiconductor material that in turn comprises layers of p-type and n-type material that define a p-n junction
15 therebetween. The epitaxial layer and the substrate are etched in a predetermined pattern to define individual diode precursors, and deeply enough to form mesas in the epitaxial layer that delineate the p-n junctions in each diode precursor from one another. The substrate is then grooved from the side of the epitaxial layer and between the mesas to a predetermined depth to define side portions of diode
20 precursors in the substrate while retaining enough of the substrate beneath the grooves to maintain its mechanical stability. Ohmic contacts are added to the epitaxial layer and to the substrate and a layer of insulating material is formed on the diode precursor. The insulating layer covers the portions of the epitaxial layer that are not covered by the ohmic contact, any portions of the one surface of the substrate adjacent
25 the mesas, and the side portions of the substrate. As a result, the junction and the side portions of the substrate of each diode are insulated from electrical contact other than through the ohmic contacts. When the diodes are separated they can be conventionally mounted with the junction side down in a conductive epoxy without concern that the epoxy will short circuit the resulting diode. See the abstract of U.S.
30 Patent 4,966,862.

U.S. Patent 5,210,051 to Carter, Jr., entitled *High Efficiency Light Emitting Diodes From Bipolar Gallium Nitride*, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein, describes a method of growing intrinsic,

substantially undoped single crystal gallium nitride with a donor concentration of $7 \times 10^{17} \text{ cm}^{-3}$ or less. The method comprises introducing a source of nitrogen into a reaction chamber containing a growth surface while introducing a source of gallium into the same reaction chamber and while directing nitrogen atoms and gallium atoms to a growth surface upon which gallium nitride will grow. The method further comprises concurrently maintaining the growth surface at a temperature high enough to provide sufficient surface mobility to the gallium and nitrogen atoms that strike the growth surface to reach and move into proper lattice sites, thereby establishing good crystallinity, to establish an effective sticking coefficient, and to thereby grow an epitaxial layer of gallium nitride on the growth surface, but low enough for the partial pressure of nitrogen species in the reaction chamber to approach the equilibrium vapor pressure of those nitrogen species over gallium nitride under the other ambient conditions of the chamber to thereby minimize the loss of nitrogen from the gallium nitride and the nitrogen vacancies in the resulting epitaxial layer. See the abstract of U.S. Patent 5,210,051.

The coating of a phosphor on an LED may further complicate light extraction problems. In particular, it may be desirable to provide a phosphor for an LED, for example to provide solid-state lighting. In one example, LEDs that are used for solid-state white lighting may produce high radiant flux output at short wavelengths, for example in the range of about 380nm to about 480nm. One or more phosphors may be provided, wherein the short wavelength, high energy photon output of the LED is used to excite the phosphor, in part or entirely, to thereby down-convert in frequency some or all of the LED's output to create white light.

As one specific example, ultraviolet output from an LED at about 390nm may be used in conjunction with red, green and blue phosphors, to create white light. As another specific example, blue light output at about 470nm from an LED may be used to excite a yellow phosphor, to create white light by transmitting some of the 470nm blue output along with some secondary yellow emission occurring when part of the LEDs output is absorbed by the phosphor.

As is well known to those having skill in the art, at least two techniques may be used to incorporate phosphor material into a light emission path of an LED. In one technique, the phosphor may be suspended in the packaging and/or encapsulation that is provided with the LED, so that the phosphor is maintained in proximity to the LED.

In an alternative approach, the phosphor material is coated on the LED itself. When coating a phosphor, a liquid binder, such as an epoxy, may be used, in which one or more phosphors is suspended. The phosphor-containing binder may be dispensed onto the LED prior to dispensing and curing a clear encapsulation epoxy. LEDs that
5 employ phosphor coatings are described, for example, in U.S. Patents, 6,252,254; 6,069,440; 5,858,278; 5,813,753; and 5,277,840.

In view of the above discussion, improved light extraction techniques may be desirable for LEDs, especially LEDs that are fabricated from silicon carbide, that are fabricated from gallium nitride on silicon carbide and/or that include a phosphor
10 coating.

Summary of the Invention

Light emitting diodes according to some embodiments of the invention include a substrate having first and second opposing faces, and a diode region on the first
15 face. The sidewall(s) of the light emitting diode extend at an oblique angle, rather than a 90° angle, from the second face towards the first face. In some embodiments, the oblique angle is an obtuse angle. In some embodiments, the oblique sidewall may extend from the second face to adjacent the diode region. A conformal phosphor-containing layer is included on at least a portion of the oblique sidewall. In other
20 embodiments, the phosphor-containing layer is also included on the second face. According to some embodiments of the invention, by providing an oblique sidewall adjacent the second face, more uniform phosphor-containing coatings may be obtained compared to light emitting diodes that have a vertical (orthogonal) sidewall adjacent the second face.

25 Light emitting diodes may be fabricated, according to some embodiments of the present invention, by conformally coating a sidewall, which extends at an oblique angle from a second face of a substrate towards a first face of the substrate, with a layer containing phosphor. The second face also may be conformally coated.

Brief Description of the Drawings

30 Figure 1A is a cross-sectional view of a light emitting diode including a vertical sidewall adjacent a second face thereof.

Figure 1B is a cross-sectional view of a light emitting diode including a vertical sidewall adjacent a second face thereof that is coated with a phosphor-containing layer.

5 Figure 2A is a cross-sectional view of an LED that includes an oblique sidewall adjacent the second face thereof according to some embodiments of the present invention.

Figure 2B is a cross-sectional view of an LED that includes an oblique sidewall adjacent the second face thereof that is coated with a uniform thickness phosphor-containing layer according to some embodiments of the present invention.

10 Figure 2C is a cross-sectional view of an LED that includes an oblique sidewall adjacent the second face thereof including a multi-layer contact structure, and that is coated with a uniform thickness phosphor-containing coating according to some embodiments of the present invention.

15 **Detailed Description**

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. However, this invention should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, the thickness of layers and regions are exaggerated for clarity. Like numbers refer to like elements throughout. It will be understood that when an element such as a layer, region or substrate is referred to as being "on" or extending "onto" another element, it can be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" or extending "directly onto" another element, there are no intervening elements present.

Embodiments of the invention now will be described, generally with reference to gallium nitride-based light emitting diodes on silicon carbide-based substrates. However, it will be understood by those having skill in the art that many embodiments of the invention may be employed with any combination of a substrate that is non-absorbing or transparent to the emitted light. In some embodiments, the refractive index of the substrate is greater than that of the diode. Accordingly, combinations can include an AlGaInP diode on a GaP substrate; an InGaAs diode on

a GaAs substrate; an AlGaAs diode on a GaAs substrate; an SiC diode on an SiC Substrate, an SiC diode on a sapphire (Al_2O_3) substrate; and/or a nitride-based diode on a gallium nitride, silicon carbide, aluminum nitride, zinc oxide and/or other substrate.

5 Many examples of such LEDs are described in Application Serial No. 10/057,821, filed January 25, 2002, to Slater, Jr. et al., entitled *Light Emitting Diodes Including Substrate Modifications for Light Extraction and Manufacturing Methods Therefor*, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein.

10 Figure 1A is a cross-sectional view of LEDs with orthogonal sidewalls adjacent a second face thereof. In particular, referring to Figure 1A, these LEDs include a substrate **100**, such as a silicon carbide substrate **100**, having first and second opposing faces **100a** and **100b**, that is transparent to optical radiation in a predetermined wavelength range. As used herein, the term "transparent" means that
15 optical radiation in the predetermined wavelength range can pass through the material without being totally absorbed or totally reflected. A diode region **110** is on the first face, and is configured to emit light in the predetermined wavelength into the substrate **100** upon application of voltage across the diode region **110**. The diode region **110** may comprise silicon carbide, gallium nitride and/or other materials, such
20 as is described in the aforementioned Application Serial No. 10/057,821.

Still referring to Figure 1A, the substrate **100** includes one or more sidewalls that include a first portion **100c** that is adjacent the second face **100b** and is orthogonal thereto, as shown by the 90° angle in Figure 1A. A second portion **100e**, adjacent the first face **100a**, is orthogonal thereto. A third portion **100d** between the
25 first and second portions **100c** and **100e** is oblique, making an angle of, for example, 30° with an extension of the second portion **100e**. Although Figure 1A is not drawn to scale, dimensions for one embodiment are illustrated in Figure 1A. Thus, in the embodiment illustrated in Figure 1A, the first face may be about $300\mu\text{m}$ wide, and the second face may be about $200\mu\text{m}$ wide. The first portion **100c** of the sidewall may be
30 about $135\mu\text{m}$ thick, the second portion **100e** of the sidewall may be about $25\mu\text{m}$ thick, and the oblique portion **100d** of the sidewall may be about $90\mu\text{m}$ thick, so that the surface of the oblique portion **100d** is about $105\mu\text{m}$ long. The total thickness of the LED is about $250\mu\text{m}$.

Referring now to Figure 1B, LEDs of Figure 1A including a phosphor-containing coating **120** are shown. As shown in Figure 1B, it may be difficult to coat the second face **100b** or the first (vertical) portion **100c** of the sidewall as thick as the third (oblique) portion **100d** of the sidewall. More specifically, in order to obtain sufficient coverage on the first (vertical) portion **100c** of the sidewall, excess phosphor-containing binder may be used, which may still provide poor coverage on the second face **100b**, and may also cause excessive amounts of the phosphor-containing binder to flow down onto the third (oblique) portion **100d** of the sidewall. The poor coverage of the phosphor-containing coating **120** on the second face **100b** may allow too much blue emission to be radiated directly from the LED without passing through any or enough of the absorbing yellow phosphor. Moreover, the excessive amount of phosphor that may flow down onto the third (oblique) portion **100d** of the sidewall may result in too little blue emission from the lower portion of the LED. The secondary yellow emission may occur underneath the excessively thick layer of phosphor-containing binder on the third (oblique) portion **100d** of the sidewall, yet is absorbed by the upper portion of the phosphor-containing binder which may result in reduced conversion efficiency for the phosphor-coated LED and/or may result in large angular dependence by Color Correlated Temperature (CCT).

Some embodiments of the present invention, which are described in Figures 2A-2C, can allow at least some of the emitting surfaces of an LED to be covered with a nearly conformal phosphor-containing layer of substantially uniform thickness. This more conformal coverage can produce a desired spectrum of light, while also allowing more radiant flux to be emitted from the phosphor-coated LED.

Figure 2A is a cross-sectional view of LEDs according to some embodiments of the present invention. As shown in Figure 2A, these LEDs include a semiconductor substrate, such as a silicon carbide substrate, having first and second opposing faces **200a** and **200b**, that is transparent to optical radiation in a predetermined wavelength range. A diode region **210** is on the first face **200a**, and is configured to emit light in a predetermined wavelength range into the substrate **200**, upon application of voltage across the diode region **210**. The diode region **210** may comprise silicon carbide, gallium nitride and/or other materials, such as is described in the aforementioned Application Serial No. 10/057,821.

As also shown in Figure 2A, at least one sidewall of the LED includes a first oblique portion **200d** adjacent the second face. The oblique portion **200d** forms a non-orthogonal angle, for example an obtuse angle such as an angle of 120°, with the second face **200b**. In some embodiments, the oblique portion **200d** may extend from the second face **200b** adjacent or all the way to the first face **200a**. In other
5 embodiments, a second orthogonal portion **200e** may be present adjacent the first face **200a**. In some embodiments, the oblique portion **200d** is a planar oblique portion, to provide a continuous taper that extends from the second face **200b** towards the first face **200a** and, in some embodiments, from the second face **200b** all the way to the
10 first face **200a**. In other embodiments, the oblique portion **200d** may be curved (nonplanar), include multiple planar segments, and/or be textured.

Although Figure 2A is not drawn to scale, dimensions for one embodiment of the present invention are shown. In particular, the first face **200a** may be about 300µm wide, whereas the second face **200b** may be about 125µm wide. The first
15 oblique portion **200d** of the sidewall may be about 150µm thick, to provide a surface length of about 173µm. The second orthogonal portion **200e** may be about 25µm in thickness. Accordingly, the total thickness of the LED may be about 175µm.

The fabrication of LEDs with an oblique sidewall adjacent the second face is well known to those having skill in the art, and is described, for example, in U.S.
20 Patent 5,087,949, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein.

Comparing embodiments of Figures 2A and 1A with the dimensions shown in these figures, LEDs of Figure 2A have a lower (flatter) profile, and a continuous tapered oblique sidewall portion **200d** from the second face **200b** almost to the first
25 face **200a**. Stated differently, there is no post with first vertical portions **100c**. Embodiments of Figure 2A may be fabricated using a thinner silicon carbide substrate than used for embodiments of Figure 1A. In particular, substrates **100** as illustrated in Figure 1A may be about 250µm thick, whereas substrates **200** in some embodiments of the present invention as illustrated in Figure 2A may be about 175µm thick. It will
30 be understood, however, that in other embodiments, the substrate need not be thinner, and the taper angle and/or other parameters may be adjusted accordingly.

In addition, a saw blade that is used for the saw/break process with an LED of Figure 1A that is fabricated on a 300µm pitch, may be about 100µm wide. The tapered facet created by the saw in Figure 1A (third portion **100d**) and in

embodiments of the present invention as shown in Figure 2A (first oblique portion **200d**), may be about 30° from normal relative to the first face **100a**, **200a**. However, the width of the saw blade in some embodiments of the present invention as shown in Figure 2A may be about 175μm wide. The wider blade and the thinner substrate **200** can produce a continuously tapered first oblique portion **200d** of the sidewall starting at the second face **200b** where the wire bond is formed and extending to the first face **200a**, within about 20μm to about 30μm, shown in Figure 2A as within about 25μm. In both Figures 1A and 2A, the bottom 20μm to 30μm adjacent the first face **100a**, **200a** is relatively vertical, as these portions **100e/200e** may be broken through to singulate the die.

Continuing with the comparison of Figure 2A and Figure 1A, in some embodiments, the first face **200b** of Figure 2A is 125μm², whereas the first face **100b** of Figure 1A is about 200μm² atop a vertical post that is between about 130 and 140μm (shown as 135μm in Figure 1A) tall. The first oblique portion **200d** has a total length of about 173μm in Figure 2A, whereas the intermediate tapered portion **100d** has a total length of about 105μm. Looking at the height dimension, the first oblique portion **200d** is about 150μm of 175μm total height in Figure 2A, whereas in Figure 1A, the third portion **100d** is about 90μm of the 250μm total height.

Referring now to Figure 2B, a phosphor-containing layer **220** is coated on the oblique sidewall **200d** and also may be coated on the second face **200b**. In some embodiments, the phosphor-containing layer may include a binder, such as an epoxy, a silicon-based matrix and/or other solvent. The phosphor may be cerium-doped YAG and/or other conventional phosphors. However, other conventional binders and/or phosphors may be used depending on the application. The phosphor may be coated on the LED by screen printing, evaporation (sputter, e-beam, thermal, CVD, electrostatic and/or electrophoretic deposition), dipping, spin coating and/or other techniques. The phosphor-containing layer **220** then may be cured at between about 50°C and about 200°C for about several seconds to several hours. The thickness of the phosphor-containing layer **220** may range between about 2μm and about 100μm, in some embodiments of the invention. However, other thicknesses may be used. The thickness that is used may be selected to reduce or minimize self-absorption and/or scattering and may depend on the coating process, the density of the phosphor and/or the desired application. Moreover, a coating process or combinations of

coatings processes may be selected to control the thickness of the phosphor on the oblique sidewall **200d** compared to the second face **200b**.

The oblique portion **200d** of the sidewall can improve the uniformity of the phosphor-containing layer **220**, as shown in Figure 2B. This can improve the light conversion compared to LEDs of Figure 1B.

In some embodiments, the increased light output for embodiments of Figure 2B can be between about 10% and about 15% compared to embodiments of Figure 1B. In addition to the increased power or radiant flux, embodiments of the invention as shown in Figure 2B can have no substantial vertical sidewall except for the second portion **200e** through which the die are broken. This, in conjunction with the reduced height, can allow uniform phosphor coverage to be obtained over the entire first oblique portion **200d** and/or over the first oblique portion **200d** and the second face **200b**. Accordingly, improved blue and yellow transmission conversion efficiency can provide improved color rendering of a white light source in some embodiments of the present invention, compared to embodiments of Figure 1B. Moreover, by reducing the thickness of the substrate, improved (lowered) static resistance of the LED may be obtained, which can lead to improved in-the-wall plug efficiency. Finally, it will be understood that parameters of the oblique portion **200d**, such as length, angle and/or topography may be adjusted to provide a desired light output with a given phosphor and/or coating process.

Figure 2C illustrates other embodiments of the present invention, including a reflective substrate contact **230** on the second face **200b** of the substrate **200**. As shown in Figure 2C, in some embodiments, the substrate contact **230** can completely cover the second face **200b**. This can reduce or eliminate the possibility of transmitting light directly from the LED without passing through any of the phosphor-containing layer **220**. A contact **230** that covers the entire second face **200b** may also reduce the tendency to over-dispense the binder, in order to complete coverage of the second face **200b**. It will be understood that, in other embodiments of the invention, the substrate contact **230** need not cover the entire second face **200b**. In some embodiments of the present invention, the phosphor-containing layer **220** need not be present on the substrate contact **230**, or may be present in reduced thickness, compared to the first oblique portion **200d**, as shown in Figure 2C. At least some of the phosphor-containing layer **220** may be removed from the contact **230**, using conventional techniques. It also will be understood that some embodiments of the

invention may be used in a suspended phosphor packaging to enhance the light extraction from the LED into the suspended phosphor, by, for example, blocking emission from the second face **200b** and only allowing emission from the oblique portion **200d**.

5 It also will be understood that coverage of the substrate contact **230** on the entire second face **200b** may reduce the light output compared to a substrate contact that only covers a portion of the second face **200b**. Referring again to Figure 2C, in some embodiments, a multilayer contact **230** may be provided, including a reflective layer, can at least partially compensate for this loss. For example, some substrate
10 contacts according to embodiments of the present invention may include an ohmic layer **232** comprising, for example, about 25Å of nickel, a reflector layer **234** comprising, for example, about 1000Å of silver and/or aluminum, a barrier layer **236** comprising, for example, about 500Å of platinum and/or TiN, and a bonding layer **238** comprising about 10,000Å of gold. This may be contrasted with other
15 contact/bond pads that may include titanium, platinum and gold layers. It has been found, according to some embodiments of the invention, that the loss in light output from a conventional contact may arise from the poor reflectivity of the titanium layer at the interface with the second face **200b**. In sharp contrast, according to some embodiments of the invention, the ohmic layer comprising nickel between the second
20 face **200b** and the reflective layer **234** can be made very thin, for example between about 25Å thick, in order to reduce losses. Other contact structures that may be employed are described in the aforementioned Application Serial No. 10/057,821.

 In the drawings and specification, there have been disclosed embodiments of the invention and, although specific terms are employed, they are used in a generic
25 and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.